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An Examination of Injury Criteria for Potential Application to Explosive Safety Studies

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ABSTRACT

A state-of-the-art assessment of research into and the modeling of wounding mechanisms and phenomena is described. The results of an extensive survey of the literature are presented along with recommendations for replacement of the presently used "58 ft-lb rule". The data and models located have been evaluated with respect to applicability to explosive safety studies which typically require quantification of the fragment impact hazards to personnel. Major topics for discussion include penetrating and non-penetrating injury mechanisms and models, wounding thresholds, military incapacitation criteria, and existing safety criteria, as well as recommendations for formulation of new criteria.

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1. Preface

The work described in this paper was sponsored and funded by the Department of Defense Explosive Safety Board (DDESB) in March 1983 under Project 4A665805M857.

2. Introduction

Present Department of Defense Explosive Safety Board (DDESB) doctrine establishes the acceptable fragmentation hazards to personnel exposed to accidental explosions. Presently, the acceptable limit is exposure to not more than 1/600 square feet of hazardous fragments. Current DDESB policy is to define a "hazardous fragment" as one which has at least 58 foot-pounds of kinetic energy. Clearly, the use of this, or any other injury criterion will effect the calculated distances required to limit personnel to the acceptable exposure limit.

Use of the 58 ft-lb criterion to define fragmentation hazards has been criticized in recent years because, 1) it is not based on any well defined injury classification scheme, 2) it is overly simplistic in nature, and 3) a general feeling that there must be something better available in light of all the research into wounding phenomena and effects that has taken place over the last several decades.

The objectives of this investigation were to review the literature on kinetic energy wounding, assess the state-of-the-art, determine the applicability of existing data and models to explosive safety studies, and if appropriate, recommend new criteria. In addition, since the far-field hazards relate mainly to large (ranging from a few grams to several kilograms), relatively slow moving fragments with speeds approaching their free-fall velocity, the range of variables over which the various criteria are valid was to be determined and methods for extrapolating to the mass range of interest considered. The discussion

presented here will focus on the major findings of the investigation with respect to the availability of a suitable 58 ft-lb law replacement candidate. Additional details concerning other important research not covered in this paper, along with the bibliography which resulted from the current study, can be found in a soon to be published BRL report.

3. Literature Search

The survey of the literature was conducted by a contractor, Ketron, Inc. Several hundred technical reports and journal articles were compiled, reviewed, and analyzed with the above mentioned objectives in mind. A majority of the documentation was located by querying the DTIC (Defense Technical Information Center), NTIS (National Technical Information Service), TRIS (Transportation Research Information Service), BIOSIS (Biological Research Abstracts), and MEDLINE (Medical Literature Analysis and Retrieval Systems) automated data bases. In addition, a significant amount of relevant information was obtained through numerous informal discussions with various researchers in ballistics and related fields. A comprehensive bibliography containing 304 citations was compiled from the reviewed literature.

4. Penetrating Trauma

In the search for relevant literature, a natural division seemed to occur between penetrating injury and non-penetrating injury data. Accordingly, the documents reviewed were categorized as relating to either one or the other. The overwhelming majority of data and models located pertain to research into penetrating injury phenomena. The following discussion will focus on only a few of the criteria which were established as a result of this research.

4.1. 58 Ft-Lb Criterion

The literature abounds with references to the 58 ft-lb energy criterion. Rohne is usually given credit for establishing this criterion which was probably intended as nothing more than a rough rule of thumb. The date usually attributed to its origin is 1906. The actual quote, translated from the 1906 article[1] by Rohne is "To remove a human from the battlefield, a kinetic energy of 8 mkg is sufficient according to the prevailing view in the German artillery community;....". Actually, an earlier article by Rohne, written in 1896 under the same title, contains the same statement; in neither case does he cite any data, experimental or otherwise, to substantiate this view. Interestingly, in a subsequent paragraph, he states that "Horses require a larger impetus to incapacitate them. Colonel Langlois set forth a kinetic energy of 19 mkg in his report "L'artillerie de campagne en liason avec les autres armes",... Again, it is unfortunate that the basis for these statements is not explained. Rohne, while not discussing the validity of the 58 ft-lb criterion, used it to determine ranges at which various military rifles ceased to be effective.

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[1] Rohne, H.; Schiesslehre fur Infanterie, 1906.

While the exact origin and basis for the 58 ft-lb figure remains obscured, other researchers have considered its validity as a criterion with varying results. Sterne[2], for example, in 1955, suggested that Rohne's criterion applied to lethality rather than to a sublethal effect. Indeed, penetrating injury research shows that lethal injuries can occur at impact kinetic energy levels significantly less than 58 ft-lbs. Without giving additional consideration to other parameters such as missile shape, size, mass, and possibly impact location, energy based hazard assessments can be misleading.

4.2. Incapacitation Criteria

In the years since Rohne, numerous researchers have investigated projectile induced kinetic energy wounding usually in hopes of relating, in some fashion, some form of ballistic dose to the projectile's casualty producing potential. The U.S. Army's incapacitation criteria, which resulted from extensive research conducted over the last three decades, were established to predict the incapacitating effects of wounding by fragmenting munitions, bullets, and flechettes. Certain of these criteria have, on occasion, been applied to hazard type analyses, but in general they are used as effectiveness criteria in the context of weapon system analyses. Briefly, the approach taken to establish these criteria was as follows.

An initial set of four steel fragment simulators was chosen to represent the class of munition fragments of interest. The projectile masses and the velocities at which they were assessed are shown in the following table.

Table 4-1. Incapacitation Projectile Data Base

Projectile	Mass	Experimental Striking Velocities
0.85 gr, steel sphere	0.055 gram	305, 914, 1524 meters/second
2.1 gr, steel cube	0.136 gram	305, 914, 1524 meters/second
16.0 gr, steel cube	1.04 gram	305, 914, 1524 meters/second
225 gr, steel cube	14.58 gram	152, 305, 762 meters/second

Basically, for each of these mass-velocity combinations, firings were conducted against biological targets to generate actual wound data. The nature of the observed wounds was delineated by assigning to it a

[2] Sterne, T. E., and A. J. Dziemian; "Provisional Probabilities of Incapacitation by a Caliber 0.30 Rifle-Bullet, Ball M-2," BRLM 949, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, Dec 1955.

wound class which related incapacitation to loss of arm and leg function.

The most widely applied criteria of this type are the curves published by Kokinakis and Sperrazza in 1965[3]. The correlation relates striking mass and velocity of an impacting steel fragment to the conditional expected level of incapacitation given a single random hit. The functional form of the relationship is:

$$P(I/H) = 1 - e^{-a(mv^{A}-b)}$$

where
- e = base of natural logarithm
- m = fragment mass (grains)
- v = fragment striking velocity (ft/sec)
- A,a,b,n = fitted constants which depend on tactical role, time after wounding, and body part hit.

Since these criteria are based upon the physical requirements and tactical functions related to infantry soldiers in the assault, defense, reserve, and supply roles, it would be inappropriate to apply them to situations involving threshold injury levels to non-military personnel.

4.3. Other Penetrating Trauma Models

In 1967, Kokinakis and Sperrazza[4] published data on the ballistic limits of skin and clothing, based on experimental firings of steel projectiles. Until recently, this skin penetration criterion was used by the U.S. Army as the "official" safety criterion for assessing threshold fragmentation hazards. However, in 1978 Lewis[5], et al developed an empirical formula for estimating the probability of skin penetration by various projectiles, including low density fragments. Of interest to

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[3] Kokinakis, W. and Sperrazza; " Criteria for Incapacitating Soldiers with Fragments and Flechettes," BRL Report 1269, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, January 1965, (CONFIDENTIAL).

[4] Sperrazza, J. and W. Kokinakis, "Ballistic Limits of Tissue and Clothing," BRL TN 1645, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, January 1967.

[5] Lewis, J. H., P. A. Coon, V. R. Clare, L. M. Sturdivan; "An Empirical/Mathematical Model to Estimate the Probability of Skin Penetration by Various Projectiles," ARCSL-TR-78004, U.S. Army Armament Research & Development Command, Chemical Systems Laboratory, Aberdeen Proving Ground, MD, 1978.

them was the environmental debris such as rocket motor fragments and other secondary projectiles that pose a hazard to personnel. Backblast debris from small rocket-motor launched weapons could include wood fragments from vegetation and structures, metal fragments from the weapon, rocklike fragments from stone or concrete structures and stones from the ground. Accordingly, they included in their investigation three sizes of wood cylinders having diameters and lengths equal to 0.5 inch (1.27 cm), 1.0 inch (2.54 cm), and 1.5 inch (3.81 cm) and irregular gravel weighing approximately 2 grams. Other missiles were 4 grain (0.259 gram), 16 grain (1.035 gram), and 64 grain (4.14 gram) steel cubes, a 0.85 grain (0.055 gram) steel sphere and a 16 grain (1.035 gram) tungsten cube. These projectiles were fired at sections of goat skin backed with 20 percent gelatin at 10 degrees C. Striking velocity was treated as a test variable.

One objective of the study was to determine the probability of complete skin perforation (full-thickness skin laceration) since the authors had equated this occurrence to a hazardous condition- the assumption being that given a complete penetration of the skin layer, the potential for deeper penetration into various parts of the body also exists. Since a fragment perforates or fails to perforate the skin, the Walker - Duncan Method[6] could be used to estimate the probability in terms of a single variable X defined by some function of the test variables. In this instance, the authors selected for their model

$$X = \ln [(MV^2)/A]$$

where m = mass of the projectile (grams)
v = velocity of the projectile (meters/sec)
A = presented area of the projectile (sq cm).

The Walker-Duncan estimation is then given by

$$P = \frac{1}{1 + \exp[-(a + bx)]}$$

where: a and b are curve fitting constants
and x is as defined above.

Employing curve fitting techniques, the authors determined a and b values for the targets shown in Table 4-2.

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[6] Walker, S. H. and D. B. Duncan; "Estimation of the Probability of an Event as a Function of Several Independent Variables", Biometrika 54:167-179, (1967).

Table 4-2 Logistic Function Coefficients

Target	a	b
Bare Skin	-28.42	2.94
Two-Layer Uniform	-48.47	4.62
Six-Layer Uniform	-50.63	4.51

Probability curves for skin penetration as a function of ln $[(MV^2)/A]$ are shown in Figure 4.1.

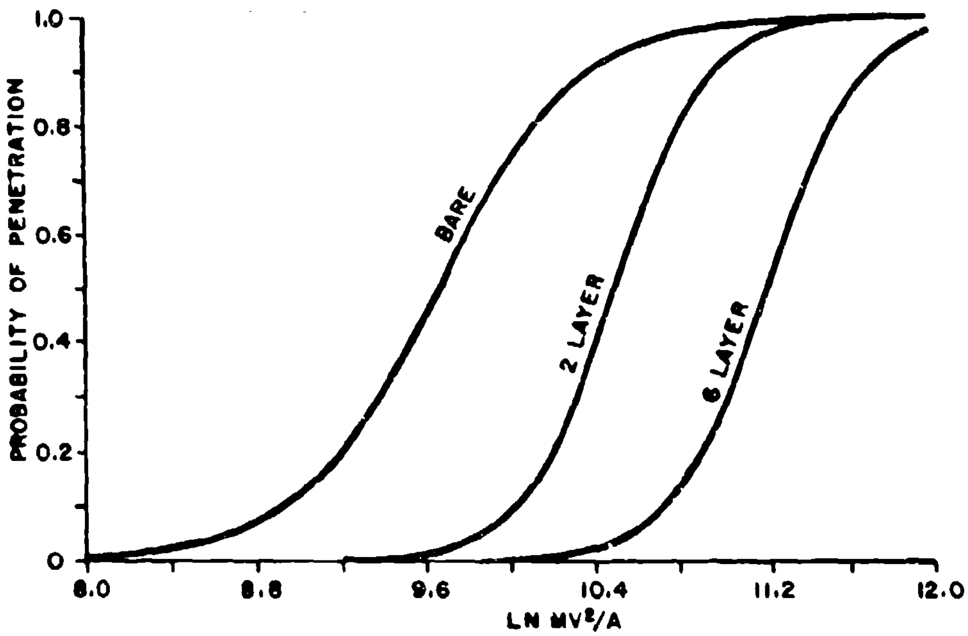

Figure 4.1 Walker-Duncan Curves Estimating the Probability of Skin Penetration as a Function of Projectile Parameters. (Reproduced from Reference 5).

5. Non-Penetrating Trauma

Although penetration is the primary damage mechanism of interest here, it was felt that the potential for injury from non-penetrating missiles exists as well. Non-penetrating injury, or blunt trauma, generally refers to any injury caused by a victim either striking or being struck by a non-piercing object. Objects causing projectile induced blunt trauma are characterized by their low velocity, lack of cutting and piercing features and size.

Most of the research pertaining to projectile-induced blunt trauma has occurred since the passage of The Omnibus Crime Control and Safe

Streets Act of 1968. Much of the research was sponsored by The National Institute of Law Enforcement and Criminal Justice and performed by multi-disciplined teams of researchers from the U.S. Army's Biophysics Laboratory located at Edgewood Arsenal (EA), Maryland and Land Warfare Laboratory (LWL) at Aberdeen Proving Ground Maryland, and various contractors.

The LWL team of Shank, Thein, Campbell and Wargovich conducted valuable research into the physiological response to the effects of non-lethal weapons[7]. An interesting part of their work involved the classification system they established for measuring these responses.

With regards to the availability of injury criteria for non-penetrating missiles the four-parameter model of Clare, et al[8], apparently represents the "state of the art" in blunt trauma modeling. Given knowledge of the input parameters, (projectile mass, velocity and diameter and target (body) mass) the model predicts the probability of lethality as a result of impact to the thorax. Their model is of the form:

$$P(r) = f(mv^2)/wD)$$

where $P(r)$ = probability of response (death, serious injury, etc)
m = mass of projectile in grams.
v = impact velocity of the projectile in meters/second.
w = body mass of the animal in kilograms.
D = diameter of the projectile in centimeters.

The same model, with appropriate adjustment of the discriminant line intercept, was extended by the authors to fracture/no-fracture data for the liver.

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[7] Shank, E. B., B. K. Thein, D. Campbell and M. J. Wargovich; "A Comparison of Various Less Lethal Weapons," LWL TR-74-79, U.S. Army Land Warfare Laboratory, Aberdeen Proving Ground, MD, June 1974.

[8] Clare, V. R., J. H. Lewis, A. P. Michiewicz and L. M. Sturdivan; "Handbook of Human Vulnerability Criteria Chapter 9. Projectile-Induced Blunt Trauma," EB-SP-76011-9, Department of the Army, Headquarters, Edgewood Arsenal, Aberdeen Proving Ground, MD, May 1976.

As shown in Figures 5.1 and 5.2, the model discriminates between low, medium, and high regions of response/no response. The authors emphasize that they consider the model to be provisional, pending availability of additional data for further validation.

6. Applicability to Explosive Safety

The relevancy of models described in the previous sections can be summarized from an examination of Figure 6.1. To facilitate comparisons of the various relationships, the masses and velocities corresponding to each model's predicted measure were determined. For example, for line B, the masses and velocities are those which correspond to a 50% probability of skin penetration (for steel cubes) according to the model of Lewis.

The presently employed 58 ft-lb law (line A) is shown in comparison with two pairs of penetrating injury relationships. The upper pair, represented by lines B and C, are based on the skin penetration model of Lewis et al. The test mass upper bound was 4.08 grams. Line B is for steel cubes; line C was derived assuming a spherical shape factor. The second pair of lines, represented by lines D and E describe the penetration law of Sperrazza and Kokinakis. The test mass upper bound was 15 grams. Line D is based on steel cubes; line E was derived assuming a spherical shape factor. In addition, the calculated DDESB mass interval of interest[+] is shown in the shaded area.

The two lines labeled "G" represent the relationship of Clare, et al for threshold liver fracture. The bottom solid G-line most directly reflects the test data for which the average animal weight, w, was about, 11.3 kg. The upper dashed G-line is an extrapolation to a man's body weight of 70 kg. Both lines are for low density (average 1.31 g/cm^3) projectiles and the mass test data interval was from 3 grams to 381 grams. Also shown is the LWL blunt trauma relationship for the first damage level (line F).[++] The LWL relationship was not discussed here since it is not directly applicable to humans. It is included because it corresponds to a low level of injury (LWL damage level 1) and is therefore of interest from an injury threshold perspective. Unfortunately, the model is not appropriate for human body weights. With the EA model, weight of the target is an input parameter.

[+] The interval depicted represents a crude estimate of the relevant mass range based on 155 mm projectile data published by Feinstein, D. I., in "Fragmentation Hazards to Unprotected Personnel," IITRI J6176, Engineering Mechanics Division, IIT Research Institute, Chicago, IL for the Department of Defense Explosive Safety Board (DDESB), Washington, DC, January 1972.

[++] The LWL team of Shank et al used a six valued damage level grading system to describe the effects of blunt trauma wounds. Damage level 1, corresponds in general to superficial or slight damage. See reference 7 bottom of page 7.

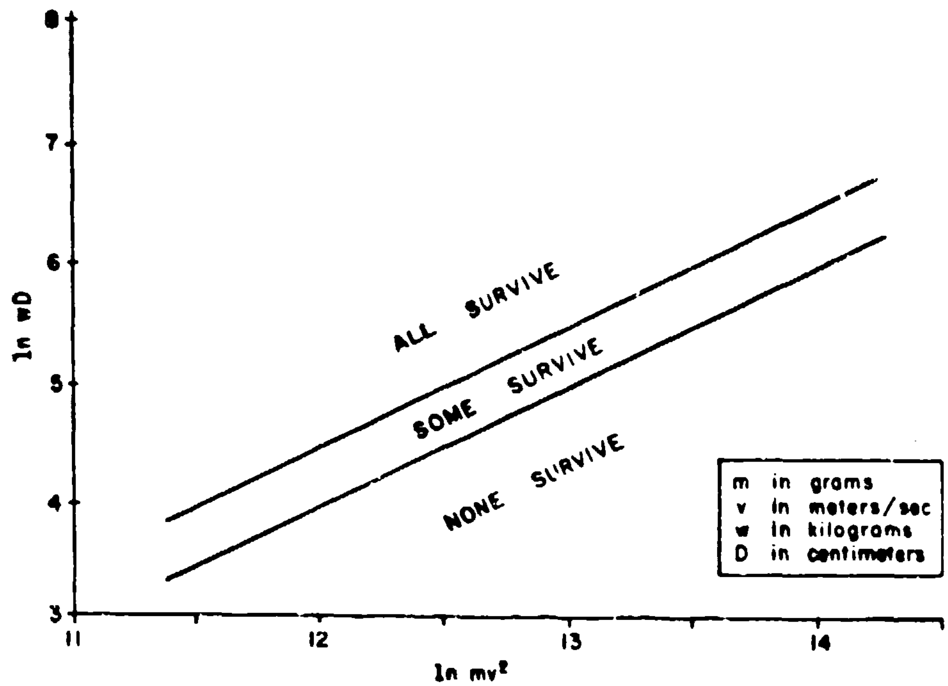

Figure 5.1 Lethal/Non-Lethal Discriminant Lines, Based on EA Four-Parameter Model Applied to Animal Blunt Trauma Data.

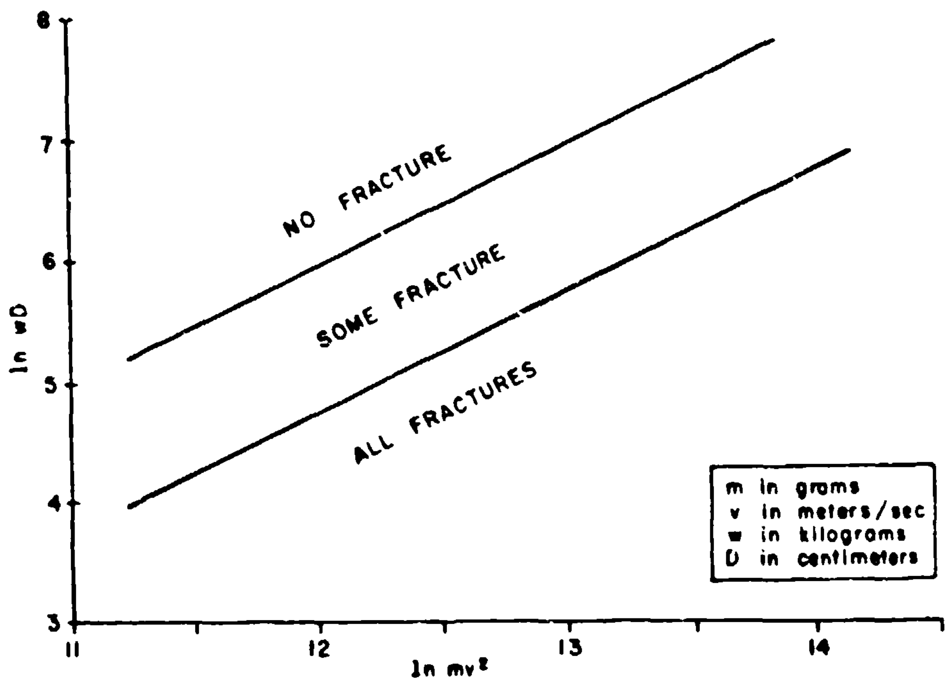

Figure 5.2 Liver Fracture/No Fracture Discriminant Lines, Based on EA Four-Parameter Model Applied to Blunt Trauma Data.

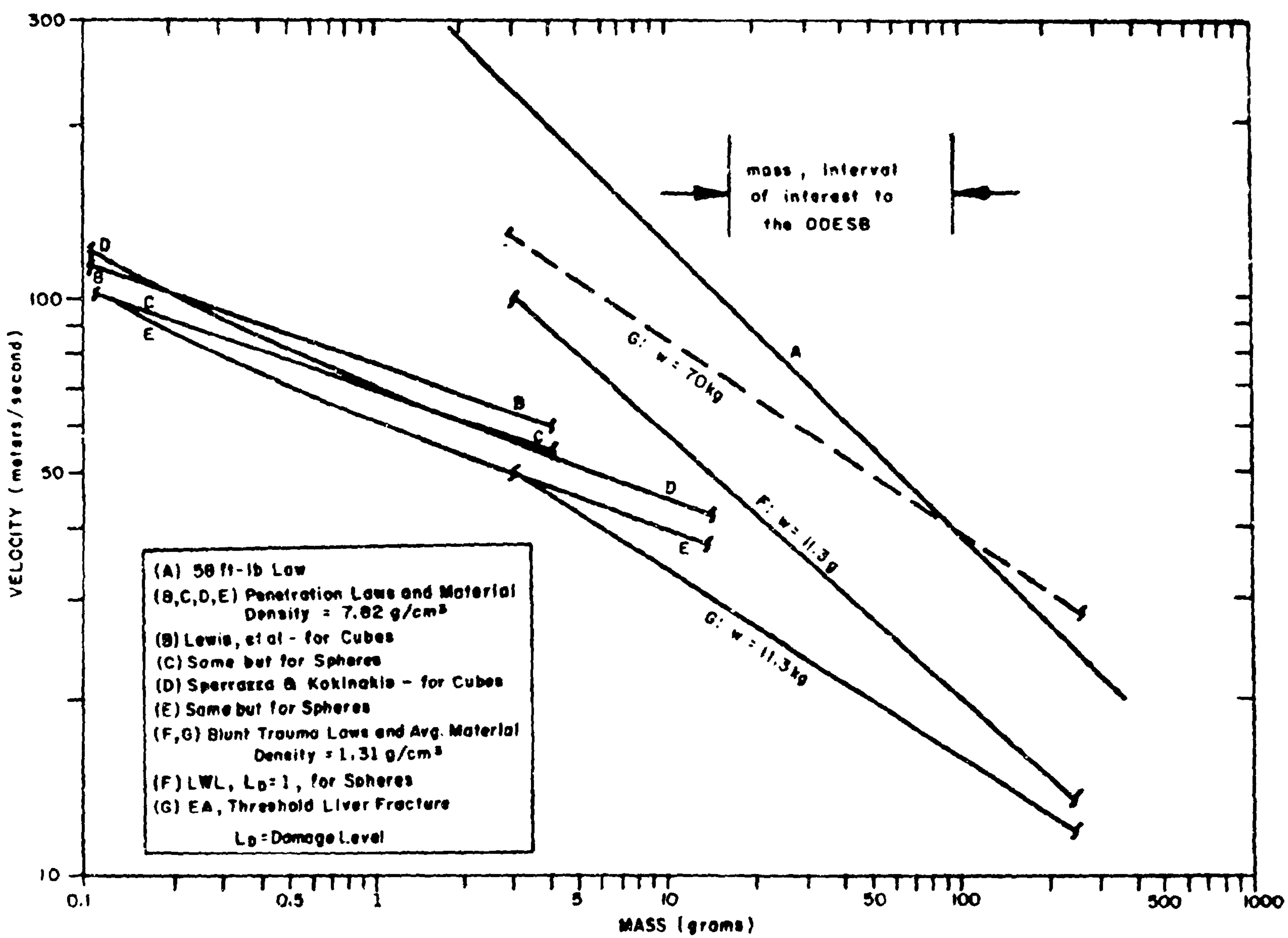

Figure 6.1 Laws, Mass Bounds on Data and DDESB Mass Interval of Interest.

7. Summary and Conclusions

In the attempt to locate criteria which represent an improvement over the currently used 58 ft-lb law, it became obvious that an accurate assessment of the hazards for typical far-field fragments by application of the various criteria located was not possible due to two noted shortcomings, namely:

1.) the lack of non-penetrating injury data for projectiles with densities greater than about 1.31 gm/cm^3,

2.) the lack of penetrating injury data for projectiles with mass greater than about 15 grams.

The above deficiencies are a result of wounding/injury research being concentrated on the effects of small, high velocity, steel projectiles. Where investigations were conducted into non-penetrating trauma, the projectiles of interest were, by design, of low density materials. The assessments and comparisons made in the analysis then are, in some cases, based on severe extrapolations of the existing data bases. For example, in comparing Lewis's skin penetration model with the 58 ft-lb rule, it was necessary to assume the model was valid for fragment masses an order of magnitude larger than those upon which the model is based. Accordingly, there is a critical need to verify the skin penetration curves in the mass ranges of interest, and the blunt trauma relationship for high density materials. Given these model validations/modifications, it is felt that a viable solution to the problem of determining far-field fragment hazards to personnel could involve simultaneous application of the two models mentioned above to quantify the potential for both penetrating and non-penetrating injury. A hazardous condition would be indicated if either criterion was met.

A methodological change of this nature would of course require a concomitant change in philosophy as to just what constitutes an unacceptable hazard to personnel. The economic, social, and political implications of adopting the skin penetration model as a replacement for the 58 ft-lb rule have not been considered in this investigation. In conclusion, we find numerous arguments against the continued use of the 58 ft-lb criterion, the strongest of which concerns its inability to predict a well defined injury level on the basis of mass and velocity alone, and suggest that after further investigation, more meaningful criteria can be formulated by validating other scientifically based models by extending and/or modifying those models through additional experimentation and analysis.